REPAIR EFFECT OF FATIGUE CRACKS INITIATED AT OUT-OF-PLANE WELDED GUSSET JOINTS USING PRE-TENSIONED CFRP STRIPS IN CONSIDERATION OF RESIDUAL STRESS

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Abstract
This paper deals with the repair of the typical fatigue cracks initiated at the out-of-plane welded gusset joints in the steel bridge using externally bonded pre-tensioned CFRP strips. The fatigue tests of three method types have been conducted as follows: the specimen without repair, with repair by non pre-tensioned CFRP strips and with repair by pre-tensioned CFRP strips. As a result, under the applied nominal stress ranges, the fatigue lives were improved drastically. In analytical evaluation, the 3D finite element analysis (FEA) was conducted in consideration the effect of the residual stress occurred at welded parts. The residual stress distribution was obtained from the experiments. The predictions of fatigue lives were analytically evaluated and compared with the experimental results.

1. Introduction

In urban highway steel bridges, fatigue damage has occurred with rapid increase in traffic and the passage of overloaded vehicles. This has raised the need for the appropriate and effective maintenance method in order to rehabilitate and maintain the steel bridge structures in service in healthy condition [1]. Regarding to this, recently, the repair method using externally-bonded CFRP strips has immensely attracted attention [2]. Moreover, rather than applying the multi-layers of externally-bonded CFRP strips, the effective repair method using externally-bonded pre-tensioned CFRP strips which utilizes the advantage of pre-tension releasing has been experimentally verified [3, 4]. However, the analytical evaluation based on finite element analysis (FEA) has underestimated fatigue lives in repaired specimens and it is necessary to consider properly the effect of the residual stress and its release control by externally bonded pre-tensioned CFRP strips in crack propagation [4]. In this paper, the repair effects for the typical fatigue cracks initiated at the welded gusset joints in steel bridges were investigated experimentally using externally-bonded pre-tensioned CFRP strips. Furthermore, the predictions of fatigue lives were analytically evaluated based on FEA in consideration of residual stress and compared with the experimental results.
2. Experimental and Analytical Procedures

2.1. Specimen Geometry and Material Properties

Fig. 1 shows the geometry and dimensions of the experimental specimen with the real size out-of-plane welded gusset joints. The both sides of the steel plate \((L1350 \times W400 \times t9 \text{ mm})\) was attached to the out-of-plane gusset plates \((L500 \times W300 \times t9 \text{ mm})\) by fillet welded joints with the leg length of 6 mm. In order to control and initiate the fatigue crack from only one side, a semi-circular hold with the radius of 50 mm was installed and full penetration weld was applied at the other side of the joint condition. Table 1 shows the material properties of steel plate, CFRP strip and epoxy resin.

![Figure 1. Specimen geometry](image)

**Table 1. Material properties**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Elastic modulus (GPa)</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel plate JIS SM400</td>
<td>202</td>
<td>305</td>
<td>434</td>
<td>37</td>
</tr>
<tr>
<td>CFRP strip</td>
<td>150</td>
<td>–</td>
<td>2808</td>
<td>1.9</td>
</tr>
<tr>
<td>Epoxy resin adhesive (Konishi E250)</td>
<td>1.5</td>
<td>–</td>
<td>30</td>
<td>–</td>
</tr>
</tbody>
</table>

2.2. Repair Methods and Experimental Conditions

The fatigue tests of three method types have been conducted as follows: the specimen without repair (PWGN), with repair by non pre-tensioned CFRP strips (PWGC) and with repair by pre-tensioned CFRP strips (PWGP). For the repair method, first, the non repaired specimen was subjected to fatigue test until the crack propagated to 25 mm as an initial crack. Then the test specimen was repaired by externally-bonded four CFRP strips \((L450 \times W50 \times t1.2 \text{ mm})\) with and without pre-tension installation. The value of the compressive force due to the release of the pre-tension was approximately 65 kN. The applied nominal stress range is 60, 80, 100 and 120 MPa \((R = 0.1)\) and the loading frequency is 3 Hz.

2.3. Residual Stress Distribution and Analytical Method

In order to consider the residual stress in analytical evaluation, the same specimen as shown in Fig. 1 was subjected to measurement of the residual stress. The residual stress distribution which is shown in Fig. 2 was obtained from the released strain value due to the cutting of specimen. The high compressive stress at the distance of ±25 mm from the center is resulted from the remaining of plastic strain due to the release of tensile residual stress when the specimen was cut from the center. This released stress was redistributed and the compressive stress was exceeded over the yield stress at crack tip. For the analytical input, the residual stress distribution was generally averaged and minimized the high value at compressive stress range, and it was finally averaged at the interval of 10mm.
The 3D FEA was conducted using MSC Marc 2013. As shown in Fig. 3, a quarter of the specimen was modelled using solid element due to the symmetry of the test specimen. The minimum element size of crack tips was 0.04 mm square. The cracks were modelled using double nodes definition. The energy release rate (ERR) was calculated using the virtual crack closure technique (VCCT) and the stress intensity factor (SIF) was evaluated. The crack propagation analysis was conducted based on linear elastic fracture mechanics (LEFM) and the evaluation of fatigue life was investigated. The relationships between the SIF range $\Delta K$ and the fatigue crack growth rate based on Paris’ law is expressed by the following equation (Eq. 1).

$$\frac{da}{dN} = C \Delta K^m$$

Here, $a$ [m] is crack length, $N$ [cycle] is number of cycles, $\Delta K$ [MPa$\times$m$^{1/2}$] is SIF range, and $C$ [m$^{1/2}$/($\text{MPa} \times \text{cycle}$)] and $m$ [no unit] are the material coefficients. The value of $C$ and $m$ were obtained experimentally from the fatigue test of the specimens cut out from the same specimen shown in Fig. 1 ($C = 1.93 \times 10^{-12}$ [m$^{1/2}$/($\text{MPa} \times \text{cycle}$)] and $m = 3.35$).
3. Results and Discussions

3.1. Relationship between Crack Length and Number of Cycles

Fig. 4 shows an example of the relationships between crack length and the number of cycles under the applied nominal stress range of 100 MPa. The pointed solid lines were obtained experimentally by the Beach Mark Method. The dash lines and solid lines were obtained analytically based on LEFM in case of with and without consideration of residual stress (no RS and RS), respectively. From the figure, in case of non repair PWGN, the experimental data can be simulated with accuracy either in case of no RS or RS. The influence of the residual stress is not considered in PWGN. In case of repair PWGC and PWGP, the fatigue life evaluation is improved when the residual stress is considered and high accuracy to the experimental result is seen in PWGC.

3.2. Repaired Effect and Prediction of Fatigue Life

Fig. 5 shows the predicted fatigue life for the propagation crack length from 25 to 100 mm. The pointed dotted lines, dash lines and solid lines are experimental result, analytical result in case of no RS and in case of RS, respectively. In case of PWGN, good estimation of fatigue life is obtained in both cases. As mentioned above, this is due to the completed release of residual stress in case of non repair specimen. On the other hand, in case of PWGC, the underestimation fatigue life in case of no RS is largely improved in consideration of residual stress in case of RS. It is considered that the release of residual stress when crack occurred is controlled by the bonded CFRP strips. The remaining residual stress assists and takes part in slowing the crack propagation. In case of no RS of PWGP, the prediction of fatigue life is found to be underestimated in high nominal stress range and overestimation in low nominal stress range. The same reason can be explained for the overestimation in high nominal stress range. For the overestimation in low nominal stress range, the loss of pre-stress is considered as the reason since the fatigue tests took long time (approx. 1 month in case of nominal stress range of 60 MPa). The loss of pre-stress might tend to be faster in dynamic behavior under fatigue test. In case of RS of PWGP, the prediction of fatigue life is improved in high nominal stress range, however, the accuracy is decreased in low nominal stress range. This requires for further investigation of pre-stress introduction in analytical evaluation.

4. Conclusions

In conclusion, the findings in this paper are summarized as follows:
1) Effect of residual stress is not considered in PWGN due to completed release of residual stress.
2) In repair PWGC and PWGP, the evaluation of fatigue life requires the consideration of residual stress due to the control of the release of residual stress by externally-bonded CFRP strips.
3) Pre-stress loss can be considered as the reason of the overestimation in low nominal stress range.

References


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